Method for warning of precipitation-induced landslides

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Abstract: Yucheng District of Ya'an City in China, the so-called rainy city of Sichuan province, is chosen as the research target for this paper. Based on rich practical data, the paper describes in-depth research into various factors affecting the occurrence of landslides, conducts an overall analysis on the relationship between the time-space distribution of landslides and rainfall, and explores the method to determine the threshold of precipitation which induces regional landsliding. It also establishes in preliminary terms the system for precipitation-induced landslide forecast and early warning. Based on the inverse modelling carried out in the research area in 2004, all approaches described are practical, feasible and can provide a scientific basis for active disaster mitigation and prevention.

- The paper advocates the CF logic regression model to address the consolidation of different data layers during the critical evaluation through GIS-based statistical analysis model and the determination of data layer superposition weight. By combining the certainty coefficient (CF) and logic regression model (Binary Logistic) and with the assistance of SPSS statistical analysis software, the factor selection, heterogeneity data consolidation and the data layer superposition weight are solved and the precision and efficiency of landslide susceptibility zoning are improved.
- Quantitative investigation has been conducted on the expressed rainfall precipitation for the rainfall threshold that induces regional landsliding, based on the logical regression coefficient. Expressions considering both the rainfall intensity and rainfall threshold have been established.
- Regional precipitation-induced landslide forecast and early warning system is established, based on the landslide risk zoning and landslide rainfall threshold.

Résumé: Le Canton de Yucheng de la Ville de Ya'an City en Chine, dénomé comme ville de la pluie de la Province du Sichuan, est choisi comme la cible de la recherche pour la thèse. Basée sur les données riches et pratiques, la thèse décrit la recherche profonde en facteurs divers affectant la situation du glissement, conduit une analyse entière dans la relation entre la distribution espace-temps du glissement et la chute de pluie, et explore la méthode pour déterminer le début de précipitations provoquant le glissement regional. Elle établit aussi péliminairement la prévision du glissement provoqué par les précipitations et un système d'alerte en avance. Basées sur un modelage inverse realize dans le domaine de recherche en 2004, toutes les approches sont pratiques, faisables et peuvent fournir une base scientifique pour l'atténuation et la prévention active du désastre.

- La these propose le model de régression logique de CF pour traiter la consolidation des couches de données différentes pendant l'évaluation critique par le model d'analyse statistique sur base de GIS et la détermination du poids de superposition de couche de données. En combinant le coefficient de certitude (CF) et le model de regression logique (Logistique Binaire) et avec l'assistance du logiciel d'analyse statistique de SPSS, la sélection de facteur, la consolidation des données de hétérogénéïté et le poids de superposition de couche de données sont résolus et la précision et l'éfficience du zonage de susceptibilité de glissement sont améliorées.
- L'investigation quantitative a été conduite dans les précipitations de chute de pluie exprimées pour le début de précipitations provoquant le glissement regional basé sur le coeficient de régression logique. Les expressions prenant en considération l'intensité de chute de pluie et le début de chute de pluie pendant la chute de pluie ont été établie.
- La prévision du glissement provoqué par les précipitations et un système d'alerte en avance est basé sur la recherche concernant le zonage de risque du glissement et le début de chute de pluie de glissement.

Keywords: landslides, forecast, rainfall**;** threshold

PREFACE

China, with its complicated geological and geographical conditions, and variable climate, is one of the countries where many geological hazards occur, incurring the injury of people and great property loss every year. It is reported that considering only the sudden-onset geologic hazards such as landfall, landslide and debris flows, caused 10499 persons dead and disappeared, 65356 injured and the property loss of 57.5 billion yuan since 1995, with the average of 1167 dead and disappeared as well as 6.4 billion yuan of property loss per year and the largest direct economic loss excesses 20 billion yuan. 90% of the landslides, landfalls and debris flows are directly induced by atmospheric precipitation or are relative to the precipitation. Precipitation is one of the major factors inducing the rapid-onset geologic hazards, for example landslides, and the induced geologic hazard features based on region, large areas of damage, simultaneity, sudden breakout and serious consequences.

Conducting research into the forecasting and early warning of these precipitation-induced landslides and establishing a scientific, complete, and practical forecasting and early warning system not only carries extensive theory-oriented significance but is also of great practical importance in effectively reducing the death and injury of people and property.

OVERVIEW OF RESEARCH AREA

Yucheng district, Ya'an city of Sichuang province, the so-called "rainy city" with its area of 1067.31km^2, is located in the west of Sichuan basin at the transition area between the west edge of yjr Sichuan basin and Qinghai-Tibetan Plateau. The average rainfall in this district for successive years remain at 1749.8mm, with the rainfall concentration of 1456.7mm from May to October, amounting for 84% of the total rainfall for the year, in particular, from July to August, the rainfall reaches 820.5mm, accounting to 47% of the yearly rainfall. The days with the rainfall above 10mm are 43.7, 17 days above 25mm and 6.7 days above 50mm.

The geomorphology in Yucheng district features high mountains, deep valleys and steep slopes, with the mountainous region as its main part. Iin this region, the land features also present compact folding growth, cracked rock mass, tectonic cranny growth, strong weathered rock and abundant residence and meanwhile the district has extensive distribution of such reason-oriented loose earth mass as residual diluvia, gravity cumulate and diluvia. The brittle sill like shale mass, semi-hard sill like sand shale interbeded rock mass, hard sill like gravel mass and hard sill like carbonatitealkaline rock mass constitute the engineering geomechanics of rock mass.

187 landslides (including landfall and debris flow) in Yucheng district were recorded from 1950 to 2003. Landslides are main seated in the Guankou Formation and Jiaguan Formation in the Cretaceous System,; in the Suining Formation and Shaximiao Formation of the Jurassic System, and in the eluvium of toe slopes in the Quaternary System. Loose earth and rock debris forms the majority of landslides, which often occur in the slopes between 20° and 45°, mainly in the 30°-40° range. The concentration of landslides occurs in the rainy season (June-September). Another factor inducing landslides is human engineering activities. Landslides are induced by road building, building construction at the slope foot, change of the land structure of the slope and planting on the slope, destroying the forest vegetation all intensify landsliding.

LANDSLIDE SUSCEPTIVITY CLASSIFICATION

GIF-based statistical analysis model is a major method to appraise the risk of distortion and instability of slides. A main problem in practice is how to consolidate information in different data layers and how to determine the weight of data layer superposition. Through a CF logic regression model, that is, the combining of the certainty coefficient (CF) and logic regression model (Binary Logistic), the factor selection, heterogeneity data consolidation and the data layer superposition weight are solved in this paper.

The risk classification of landslides is carried out by using the certainty coefficient with the primary assumption that the risk of landslide is determined by the statistic relationship between the previous landslide and the data aggregation (geology and landform) determined as the inducing factors. Future landslides will occur when the environment conditions in which the landslide has occurred are similar to the ones in which the landslide occurs. The meshing unit and homogeneous meshing are the applicable model unit type.

The following expression defines the certainty coefficient:

$$CF=\begin{cases}\dfrac{PP_\alpha-PP_s}{PP_\alpha(1-PP_s)} & if \quad PP_\alpha\geq PP_s\\[2ex] \dfrac{PP_\alpha-PP_s}{PP_s(1-PP_\alpha)} & if \quad PP_\alpha\langle PP_s\end{cases} \tag{1}$$

In this expression, PPa represents the condition probability of the occurrence of landslide in the data type a, and the proportion of the existing slide area and the unit area of data type a in the actual slide application; PPs represents the transcendent probability of the occurrence of slide in the whole research area and the proportion of the slide area and the research target area.

Through the function change in the expression 1, the change range of CF is [-1,1], the positive represents the increase of the certainty of slide, that is, if the certainty of the distortion and instability of slide is high, this area is the landslide prone area; the negative represents the reduce of the certainty, that is, if the certainty of slide distortion and instability is low, the area is with small possibility of slide occurrence; if the scale is near to zero , it represents the close of transcendent rate to the condition rate, it is impossible to determine the certainty of slide , that is whether this area is the landslide prone area has not been determined.

The analysis of the appraising factors

The factors affecting sliding in Yucheng district, Ya'an city includes seven factors in three aspects: the geologic conditions: the rock structure, geologic structure; landform and geologic features: inclination, aspect of slope, type of slope and elevation; environmental elements: vegetation. See the following Table 1 for the grouping of each factor.

Calculating the certainty coefficient of slide instability of each slide factors according to the slide occurrence frequency (condition probability: slide area in the classification /classification area) and the occurrence frequency of slide in the whole research area (transcendent probability: the total area of slide/ valley area) so as to analyze the effect and degree of each slide factor upon the slide.

Table 1. The choice and grouping of slide factors

the elements affecting slide	slide factor	grouping
geological conditions	petrofabric	□, □, □, □, □
	Geologic structure	100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1200, 1300, 1400, 1500, 1600, 1700, 1800, 1900, 2000
landform and geological features	inclination (0)	0-10, 10-20, 20-30, 30-40, 40-50, 50-60, 60-70, > 70
	Aspect of slope	north, northeast, east, southeast, south, southwest, west, northwest
	Type of slope	Dip slope, reverse slope and inclined slope, quaternary accumulation horizon
	elevation (m)	<600, 600-800, 800-1000, 1000-1200, 1200-1400, >1400
Environmental elements	vegetation	Forest land , non-forest land

Selections Of Slide Key Factors

The statistic analysis mode requires adopting the key factors affecting the distortion and instability of slide to realize the perfect effect; it is not good to consider more effecting factors. In all the slide factors, some factors have no explicit physical relationship with the distortion and instability of slide, against this context, the linear statistic analysis mode will cause big errors or even unreasonable results. Input of those factors exerting remarkable effects upon the slide occurrence will produce a favourable forecasting result. This paper adopts the method of slide certainty coefficient to determine the key factors affecting sliding.

When calculating the CF of each data layer, it needs to consolidate CF of different data layers. Assume that to consolidate the CF of two data layers and mark x and y respectively, the consolidation formula is as follows:

$$z = \begin{cases} x + y - xy, & x, y\rangle = 0 \\ \dfrac{x+y}{1-\min(|\mathrm{x}|,|\mathrm{y}|)}, & x, y\text{异号} \\ x + y + xy, & x, y\langle 0 \end{cases} \tag{2}$$

Consolidating the data layer of each factor according to the formula 2, the consolidated field is CF. Firstly consolidate the two factors in the data layers to form a new data layer, then consolidate with the third factor data layer till the consolidation completes. In order to facilitate the explanation of the consolidated results, classify CF field in the consolidation layer into six grades. See the classification standard and the significance of each layer in figure three:

Table 2. Classification of the stability of CF

No.	range of CF	description	zoning of stability
1	-1, -0.5	Small certainty of slide occurrence	the slide is impossible to occur stability
2	-0.5,-0.05	Small possibility for the slide to occur	basically being stable
3	-0.05, 0.05	CF changes at o, it is hard to determine the occurrence of slide	unclear
4	0.05, 0.3	With the potential risk of slide occurrence	latent instability
5	0.3, 0.8	It is much likely for the slide to occur	instability
6	0.8, 1.0	The slide is prone to occur	extreme instability

For the different contribution of each factor to the distortion and instability of slide, that is, the relativity of different affecting factors to the slide is different, and the susceptivity classification through superposition analysis of different factor layers is different. In order to inspect and determine the significance of slide factors, the new slides (1980-2003) have been consolidated in the slide distribution data base as the layer for testing, which represents the new slide layer in recent periods. Then conduct superposition analysis on the slide stability classification of each layer and calculate the frequency of active slide in the stability grade and its proportion in the whole active slide area, then draw a rectangle table to test the correctness of slide stability classification for determining the key factors affecting the slide.

The aspect of slide, elevation, rock mass, type of slope and the inclination are determined as the key factors affecting the risk of slide in Yucheng district through consolidation analysis.

Landslide Susceptivity Classification

Superposition analysis on the key factors layer affecting the risk of slide in Yucheng district has been conducted (the layer of aspect of slope, elevation layer, rock mass layer, the layer of intimidation type and the inclination layer) in GIS and the statistic calculation result is 1.0x105 homogenous units. The single condition classifications of each affecting factors are all contained in each homogenous units, so the units are independent for the convenience to conduct statistic analysis.

Table 3. Part of attribution of unit with uniform condition

ID	area (m^2)	CF of the aspect of slope	CF of elevation	CF of rock mass	CF of type of slope	CF of inclination
12137	0.46	-0.73073	0.19889	-0.00899	0.25538	0.32838
12138	0.56	-0.73073	-0.97861	-0.00899	0.25538	0.32838
12139	0.01	-0.21884	-0.97861	-0.00899	0.25538	0.21421
12140	0.03	-0.21884	-0.97861	-0.00899	0.25538	0.10766

The procedure was then to select local model unit at random and adopt the CF of the factor data as the independent variable of logic regression model and the slide susceptivity as the dependent variable; followed by introducing the data into the statistic analysis software of SPSS and get the logic regression model mode of slide risk in Yucheng district through the Binary Logistic regression analysis.

$$W = \frac{e^Z}{1+e^Z}$$

Of which: Z= 23.517 CFPX +26.394 CFGC + 18.718 CFYZ + 16.86 CFXP + 26.198 CFPD -6.525

W represents the slide risk probability; CFPX is the certainty coefficient of the aspect of slide; CFGC is the certainty coefficient of elevation of slide; CFYZ represents the certainty coefficient of the slide of rock mass; CFZB is the slide certainty coefficient of vegetation; CFXP is the slide certainty coefficient of the type of slope; and CFPD is the slide certainty coefficient of the inclination of she slide.

The slide risk probability in the all units in the whole district has been calculated according to the established logic regression mode and the calculated results have been divided into five grades toproduce the slide risk susceptivity map of Yucheng district in GIS.

Table 4. The slide risk classification

risk grade	classification	slide risk probability
1	stable area	<10%
2	basically stable area	10%-49%
3	latent unstable area	50%-89%
4	unstable area	90%-99%
5	extremely unstable area	100%

Inspection Of The Classification

In order to determine the correctness of the slide risk classification, the slide risk classification of Yucheng district has been inspected using 35 slides of outdoor inspection in 2003. In GIS, the space analysis has been conducted by the superstition of 35 slides and risk classification layer and the inspection results---the quantities of slide in each grade show that the extremely unstable area and unstable area contain 86% of the verified landslide, indicating that the evaluation result is in reasonable agreement with the actual landslide.

STUDY ON THE SLIDE RAINFALL THRESHOLD

Data Preparation

The exact time of slide occurrence and the rainfall at the slide spot are essential data information for the study of the relationship between the slide and rainfall in Yucheng district. In the present study, this, included the rainfall data of the seven surrounding counties of Yucheng(1996-2002), and 20 rainfall data of Yucheng (2002-2004) for establishing the slide and rainfall data base of Yucheng district of Ya'an city .

Data Selection

In Yucheng district, the rainstorm is the main factor inducing landsliding in large areas. However, we noticed that, some single slide occurs in the condition with small rainfall or no rainfall. The occurrence the slide is due to the unreasonable irrigation, and anthropogenic cutting off of the slope. In order to accurately analyze the relation between the rainfall and slide occurrence, more than two slide occurrence spots in three days (72 hours) were selected as the analysis sample. We assumed that under this condition, precipitation is the main factor inducing the occurrence of slide.

There are 142 slides in Yucheng district with exact occurrence time and sites, according to the selection principles of more than two slides in 72 hours, 85 slide sites are in accordance with the requirements.

Study On The Relation Between The Precipitation And Slide

Figure 1 is the graph of the discrete spots of the rainfall of the same day and the accumulative rainfall of the previous 15 days at 85 slide spots in Yucheng district that were selected. From the figure, we can conclude that the frequency of the occurrence of sliding is also high when the rainfall of the same day is small (<30mm). The reason is that the previous rainfall causes the earth mass on the slope to be at a state of saturation or near to saturation, when the rain falls even if small, it will incur the slide of the landslide. If under the condition that the previous rainfall is small, the slide also occurs, this is mainly due to the rainfall of the same day. Therefore, the rainfall of the same day and the previous accumulative rainfall both have great effect upon the precipitation-induced slide in Yucheng district.

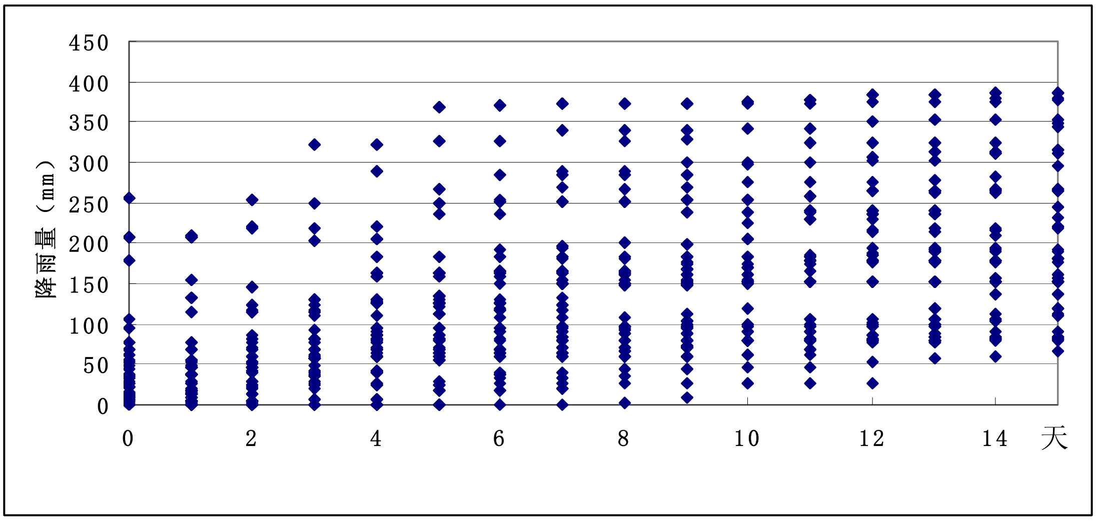

Figure 1. The figure of discrete spots of the rainfall of the same day and the accumulative rainfall for the previous 15 days in Yucheng district

Determination Of The Threshold Expressing Rainfall

As we discussed above, the slide in Yucheng district is relevant to the rainfall intensity and the previous rainfall, we can express the rainfall of the same day with the rainfall intensity but the rainfall in how many days can express the previous rainfall? So as to determine which rainfall has the closer relation with the slide, that is to discuss which variable can determine the rainfall threshold, this paper calculates the relevant coefficient of the slide occurrence and the rainfall of the same day and analyzes the relation between the slide occurrence and the precipitation through the logic regression analysis of the occurrence of slide and the previous days' rainfall.

The Binary Logistic model contained more than one independent variable can be expressed as follows:

$$P = \frac{e^Z}{1+e^Z}$$

Of which: $Z = B_0 + B_1 X_1 + B_2 \times_2 + \ldots + B_n X_n + \varepsilon$

P represents the occurrence probability of the slide

ε is the correction coefficient

In order to determine the effect of previous days' rainfall upon the slide and how significant the effect is, we select the data of the successive slide concentration spots in August, 2003 (in total 28 slide spots) and establish the data table (figure 6-3), using the logic regression mode to calculate the relevant coefficient of the rainfall of the same day and the occurrence of slide. The dependent variable represents whether the slide occurs or not, the occurrence of slide of the same day is expressed with "1"; no slide, defined with "0". The independent variable represents the rainfall of the every day before the occurrence of the slide; select the rainfall of the same day (one-day rainfall), the rainfall of the day before (2-day rainfall); rainfall of the previous two days (3-day rainfall) and the rainfall of the previous 3 days (4-day rainfall).

Table 5. Data table in Aug, 2003.

Date	Slide or not	One-day rainfall	Two-day rainfall	Three-day rainfall	Four-day rainfall	Five-day rainfall	Six-day rainfall
2003-8-23	0	32.22	10.04	21.74	3.48	1.02	1.92
2003-8-24	0	15.40	32.22	10.04	21.74	3.48	1.02
2003-8-25	1	207.00	46.50	67.60	0.60	47.50	0.60
2003-8-26	1	36.30	207.00	46.50	67.60	0.60	47.50
2003-8-27	0	7.66	47.40	97.38	15.40	32.22	10.04
2003-8-29	1	95.00	19.60	1.50	26.60	43.30	35.00
2003-8-30	0	19.57	94.37	26.20	0.67	22.87	82.70
2003-8-31	1	21.40	12.60	73.30	23.70	0.00	12.80

Introduce one-day rainfall, two-day rainfall, three-day rainfall, four-day rainfall and five-day rainfall into the SPSS software, when add the five-day rainfall, the relevant coefficient(B) is “zero”,(figure 7) indicates that the five-day rainfall has no impact upon the slide.

Table 6. Variables in the Equation

		B	Sig.
Step 1(a)	@1	.098	.044
	@2	.065	.007
	@3	.033	.038
	@4	.058	.019
	@5	.000	.998
	Constant	-10.840	.022

a Variable(s) entered on step 1: @1, @2, @3, @4, @5.

The occurrence of slide in Yucheng district is relevant to the four-day rainfall, that is, the rainfall of the same day (one-day rainfall), the rainfall of the day before (two-day rainfall), the rainfall of the previous two days(three-day rainfall), the rainfall of the previous three days(four-day rainfall).Moreover, we see that the one-day rainfall has the maximum impact upon the occurrence of the slide with the relevant coefficient of 0.098(figure seven).

According to the coefficient (B) of all the variables in figure seven, we get:

$$Z=0.098R1+0.065R2+0.033\ R3+0.058R4-10.84+\varepsilon$$

According to the classification of SPSS calculation, determine the correction coefficient ε of 2.5, combining the actual situation of slide in Yucheng district and the research purpose.

$$P=\frac{e^{0.098R_1+0.065R_2+0.033R_3+0.058R_4-8.33}}{1+e^{0.098R_1+0.065R_2+0.033R_3+0.058R_4-8.33}}$$

Of that, p is the occurrence coefficient of slide; R1 is one day rainfall , R2 is the two day rainfall , R3 is the rainfall in three days and R4 is the one in four days.

According to the analysis above, the rainfall of the same day and of the previous three days have direct impact upon the slide. The rainfall threshold expressing rainfall is determined as the rainfall of the same day (rainfall intensity) and the accumulative rainfall of previous three days (the rainfall in the previous period).

STUDY ON THRESHOLD

The acquisition of the threshold is established on the basis of rainfall statistic of the previous slide in Yucheng district. As mentioned above, the previous slide sample up to the requirement in Yucheng district totaled 85, inspect all the 53 slide spots except the ones in Aug, 2003 with the slide occurrence probability formula of four-day precipitation, of which, 12 slide spots with small occurrence probability and the inspection fails. Through analysis, we find that, the incorrect rainfall data is caused by the big distance between the slide spot and nearest rainfall measuring spot. So when determine the rainfall threshold in Yucheng district, delete the 12 spots and use the data of other 73 slide spots to analyze and determine the threshold.

According to the conclusions above, make table with discrete spots by selecting the rainfall of day when the 73 slides occur and the rainfall of the previous three days. (Figure two).

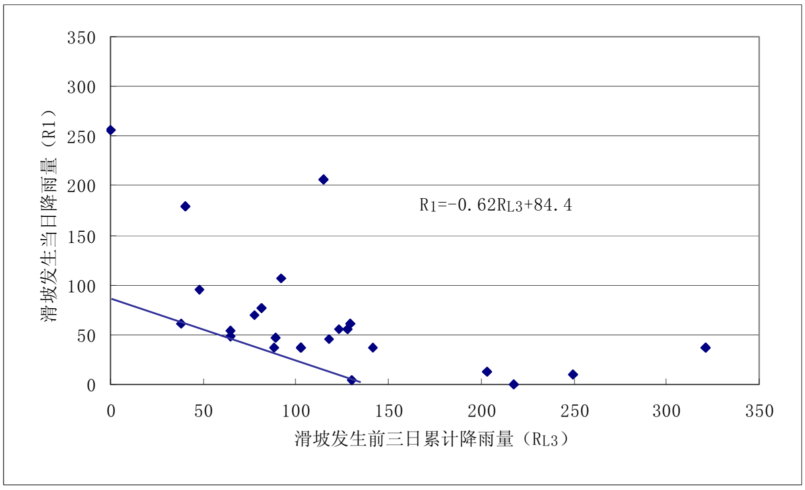

Figure 2: The discrete spot figure of the rainfall of the rainfall of the day of slid occurrence and previous three days.

Figure 2 shows discrete spot figure of the rainfall of the rainfall of the day of slid occurrence and previous three days Data shows, the expression of landslide threshold in the rainfall-induced region of Yucheng district:

R1 = -0.62RL3 + 84.4

In this expression: R1 is the rainfall of the slide occurrence day;
RL3 is the accumulative rainfall of the previous three days (figure three)

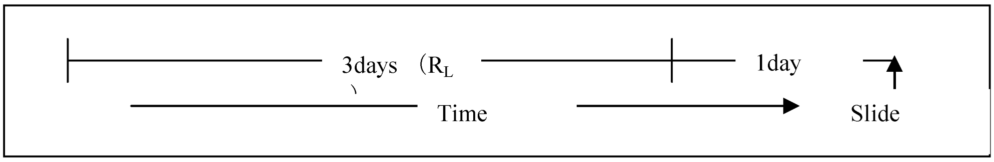

Figure 3. The relation between the rainfall of the slide occurrence day and previous three days

FORECASTING AND EARLY WARNING OF REGIONAL PRECIPITATION – INDUCED SLIDE

Based on the inspection of the atmospheric precipitation, we conduct forecast and early warning system of the slide through the time-space relation between rainfall, rainfall intensity as well as rainfall process and slide, which is the main method to conduct regional precipitation-induced slide forecast and early warning at present. This paper, using the threshold rainfall index and the calculation of the slide occurrence probability, explores the forecast and early warning of the precipitation-induced slide in Yucheng district by combining the slide susceptivity classification of Yucheng district.

Forecast and early warning index

Two indices of the regional precipitation-induced landslide early warning and forecast are the threshold rainfall index R and landslide occurrence index L. Threshold rainfall index R is used to determine the possibility of landslide occurrence, if R≥0, the slide is possible to occur in the warning area and landslide occurrence indices L can be used to determine the possible area of landslide occurrence and the likelihood.

· Threshold rainfall index R

the expression of the regional slide threshold of precipitation-induced area in Yucheng district is R1 = -0.62R3 + 84.4， we define the threshold rainfall index in Yucheng district as R: ，

R = R1 – (-0.62RL3 + 84.4) = R1 +0.62RL3–84.4

if R≥0, the slide is possible to occur;

If R＜0, the slide will not occur basically.

·slide occurrence probability P

Determine the possibility of slide occurrence through the combination of the precipitation-induced slide occurrence probability and the slide risk probability. The slide occurrence index is defined as L:

$$L = \frac{e^Z}{1+e^Z}$$

Of which, $Z=0.098R1+0.065R2+0.033R3+0.058R4-8.33+\varepsilon'$ 。

ε' is the correction coefficient after calculating the slide coefficient through considering the geologic elements and land features. According to the slide risk zoning of Section 5, that is, according to the slide risk grade of each unit of the risk probability, determine the ε' correction. See Table 7 for the specific correction coefficient.

Table 7. ε' comparison list of correction

Slide risk of	First grade	Second grade	Third grade	Fourth grade	Fifth grade
ε'	-16	-0.5	0	0.2	0.4

Early-Warning And Forecasting Grades

When the slid threshold precipitation index R＜0, there no need to warn; when the index R≥0, we need to calculate the cell slide occurrence index in the whole district, conduct forecasting and early warning in five grades according to the calculated slide occurrence index .(Table 8).

Table 8. slide forecast and early warning grade

Slide occurrence probability	Forecast and early warning grading	expression	notes
<10%	First grade	gray	Slide occurrence with small possibility
10%-50%	Second grade	blue	Slide occurrence with small possibility
50%-80%	Third grade	yellow	The slide is much likely to occur
80%-99%	Fourth grade	pink	The slide is much likely to occur
•99%	Fifth grade	red	The slide is much likely to occur

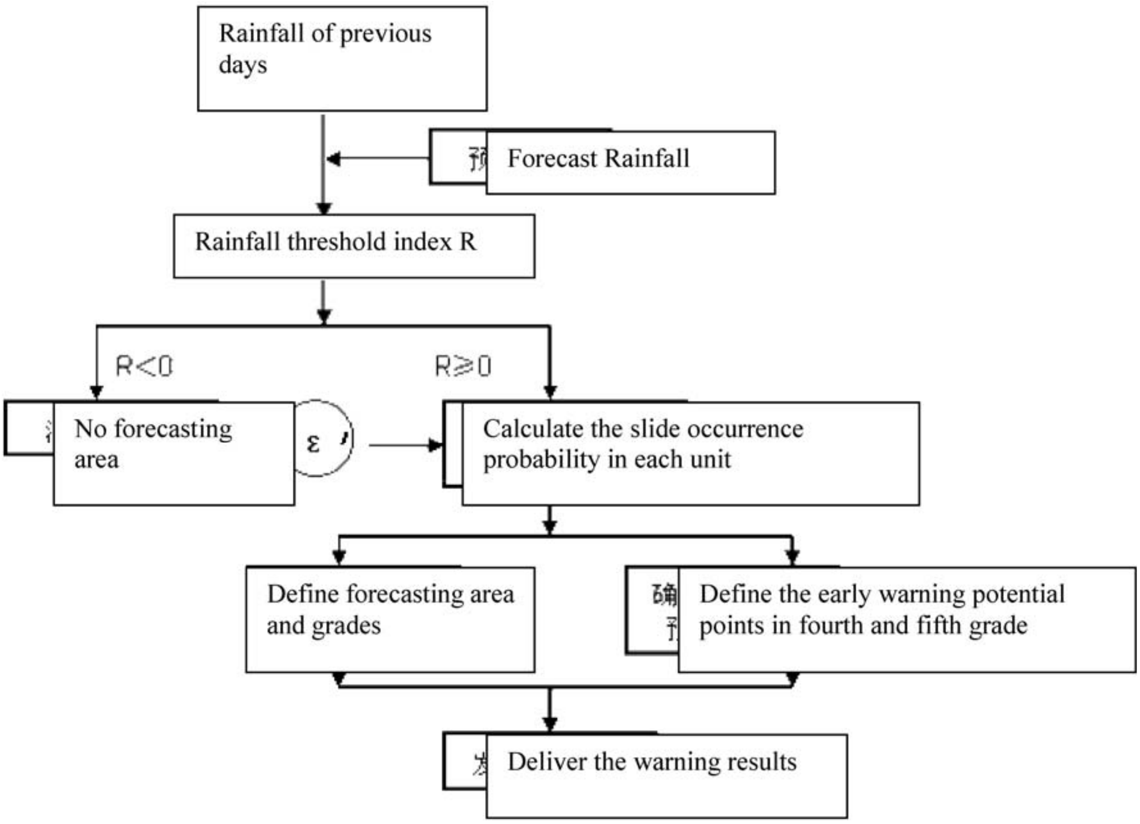

Figure 4. Flow chart of early warning and forecasting

The reverse analogue is conducted in the research area in July-September, 2004. The whole method is practical, feasible and provide scientific basis for active disaster mitigation and disaster prevention.

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